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FLOW DYNAMICS BEHAVIOUR OF A NOVEL LIQUID-LIQUID HYDROCYCLONE WITH VARYING UPPER CYLINDRICAL LENGTHS AND NUMBER OF INLETS

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ABSTRACT

The use of a liquid-liquid hydrocyclone in the downhole is one the few environmentally friendly ways by which water production can be limited, while at the same time ensure maximum recovery. The understanding of the fluid flow behaviours that bring about better separation and performance is therefore important and should not be underestimated. This work, through numerical simulation, studied the effects that the tangential inlet(s) and the height of the upper cylindrical section of a liquid-liquid hydrocyclone have on its hydrodynamics. The results showed that the single inlet hydrocyclones unlike the twin inlet types are more prone to producing asymmetrical reversal flow which meanders along the axis of the hydrocyclone. This can affect the efficiency of separation if the particles are not well segregated. The single inlet 30 mm upper cylindrical length (UCL) hydrocyclone produced the highest velocity fields that could ensure better fluid swirling and rotation, and the greatest upward core flowing pressure that could ensure better transportation of the lighter fraction concentrated at the core. Therefore, the single inlet hydrocyclone with 30 mm UCL is the best among the studied cyclonic separator types and its use for downhole oil/water separation can enhance the problem of excessive water production.

Keywords: hydrocyclone, axial velocity, tangential velocity, reversal flow.

INTRODUCTION

Hydrocyclone is a centrifugal separator which has been used as an industrial classification/separation device in industry since the 1940s. It finds wide application in the petroleum, chemical, mineral/mining, pharmaceutical, environment and food industries, etc. [1-2]. In the nineteenth century, Bretney [3], patented the first hydrocyclone and it was composed of a cylindrical section, a cone, overflow outlet and underflow outlet. The function of the cylindrical section is to stabilize the fluid flow when the fluid enters the cyclone; the cone, to enhance the centrifugal force which helps in separating the fluid particles within the hydrocyclone; the overflow outlet, to provide a way through which the lighter fraction of the fluid will leave the system and the underflow outlet to carry the heavier fraction of the fluid [1]. The simplicity of the hydrocyclone in terms of design, low in production and maintenance costs, and easy operation [4] have boosted its role in the separation of liquid-liquid products, gas-liquid products and liquid-solid products [1, 5-6]. Liquid–liquid hydrocyclones are the types used in separating one liquid from another by utilizing the advantage of the difference in their densities. Its working principle is the same as any other hydrocyclone. The use of liquid-liquid hydrocyclone to separate oil and water was first proposed by Simkin and Olney [7] and became widely accepted and popular in the 1980s [8-9]. The feed enters the hydrocyclone through the inlet(s) tangentially positioned so as to produce a vortex inside its unmoving body. The feed spirals under the centrifugal force generated within the hydrocyclone and by taking advantage of differential density between the fluid particles, separation occurs in the radial direction. Thus the particles are arranged with the lightest at the core of the hydrocyclone to the densest at the wall of the hydrocyclone [4]. A reversal flow is created at the core of the cyclone which flows counter currently to the main flow and this occurs when the underflow outlet is maintained at higher pressure than that at the overflow [6]. For separation to occur, each fluid particle within the injected fluid stream has to undergo some flow mechanisms before it is finally separated as either underflow or overflow. This flow physics is very important as the dearth of knowledge about it can lead to ineffective cyclone performance and wasted resources. This study is to showcase what happens inside a novel liquid-liquid hydrocyclone to bring to light the flow and velocity patterns that contribute to bringing about separation. The effects of the length of the upper cylindrical column and the number of inlets of the cyclone will also be known.

NUMERICAL METHOD AND CONDITIONS

Numerical simulation has become an important tool in recent times and finds application in many areas of research, industry and development. With the advent of vast computer resources, numerical simulation has become a faster and cheaper way to get promising results to problems. In this work, numerical studies were carried out using ANSYS–CFX software to study the flow fields in liquid-liquid hydrocyclone with different upper cylindrical lengths and number of inlets. Figure-1 shows the schematics of the liquid-liquid hydrocyclone employed in this paper which is a modification after Colman and Thew's type [10-11]. Two upper cylindrical lengths (UCLs) specifically, L_1 = 30 mm and 60 mm were

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considered with all the other geometrical dimensions maintained. With each of the above-mentioned hydrocyclone types, study was made into situations where the inlet is single and dual (Figure-2). The physical geometry was done using ANSYS gambit after which the geometry was imported into ANSYS–CFX for meshing and also for setting of boundary conditions (inlet velocity of 2 m/s, pressure outlet set at zero which is expressed in relative pressure and no slipping boundary condition at the walls). 3–D computational model was selected during the meshing as it gives results that can better match experimental data [12] and to improve the mesh quality, tetrahedral mesh structure shown in Figure-2 was used as it divides the flow regions more precisely and at the same time gives better results. The optimized mesh density for a reasonable solution for the different cyclone designs was around 160,000 computational cells (Figure-3). Different oil–water mixture compositions were considered. As regards the turbulence model, SSG Reynolds Stress Model was used because it is suited for complex flows and more accurate for swirling and rotational flow. It accounts for streamline curvature effects and rapid changes in strain rate as well as capturing the anisotropic character of the turbulence in the liquid-liquid hydrocyclone (LLHC) [12-14].

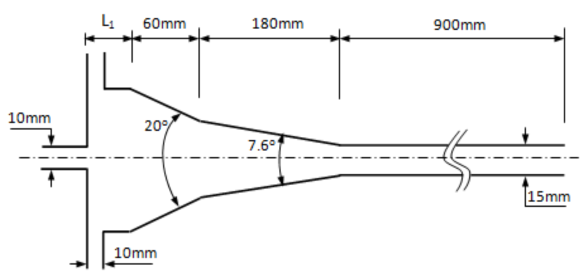


Figure-1. Hydrocyclone geometry.

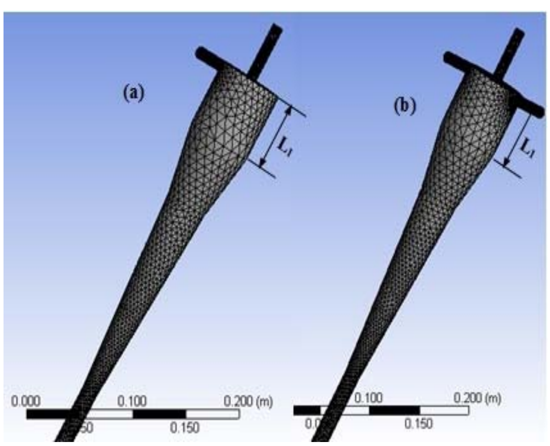


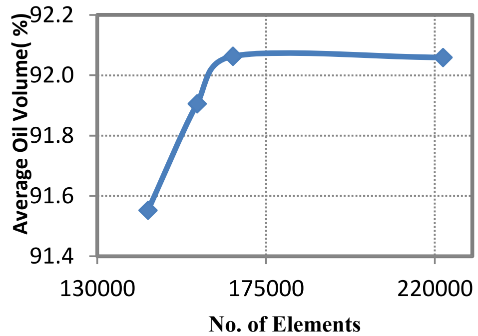
Figure-2. CFX Meshing: (a) Single inlet hydrocyclone, (b) Dual inlet hydrocyclone.

Inlet mixture composition

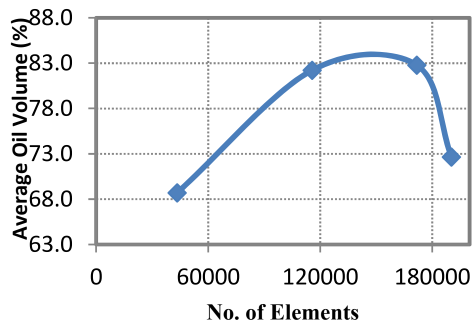
For liquid-liquid multiphase flow within the LLHC, the water is considered the continuous phase with the oil existing as the dispersed phase. The droplet size of the oil was considered to be 75 microns. Two different mixture compositions were considered and they are 25% oil-75% water and 30% oil-70% water to mimic the fluid composition in higher water cut wells where these hydrocyclones can be employed.

Governing equations

The governing partial differential equations are the mass conservation equation, Equation. (1), and the momentum conservation equation, Equation. (2) [14-15].



(a)



(b)

Figure-3. Mesh sensitivity analysis: (a) 30 mm UCL hydrocyclone; (b) 60 mm UCL hydrocyclone

$$\frac{\partial \rho}{\partial t} + \nabla.\rho u = 0 \quad (1)$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla.\left(\rho \vec{u}\vec{u}\right) = -\nabla p + \nabla.\left[\mu(\nabla u) - \frac{2}{3}\nabla.\rho \vec{u}^{2}\right] + \rho \vec{g} \quad (2)$$

ρ, p, μ, u and g represent density, pressure, molecular viscosity, flow velocity vector field and gravity respectively.

The Reynolds stress turbulence model chosen for this study can be given as Equation. (3) [14-15]:

$$\frac{\partial}{\partial t}\left(\rho \overline{u_i' u_j'}\right) + \frac{\partial}{\partial x_k}\left(\rho u_k' \overline{u_i' u_j'}\right) = P_{ij} + D_{Tij} + \Phi_{ij} - \varepsilon_{ij} + F_{ij} \quad (3)$$

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where $\overline{u_i^{'}u_j^{'}}$ is the Reynolds stress tensor, P_{ij} is the stress production term, D_{Tij} is the turbulent diffusion term, Φ_{ij} is the pressure-strain term, ε_{ij} is the viscosity diffusion term, and F_{ij} is the rotation production term.

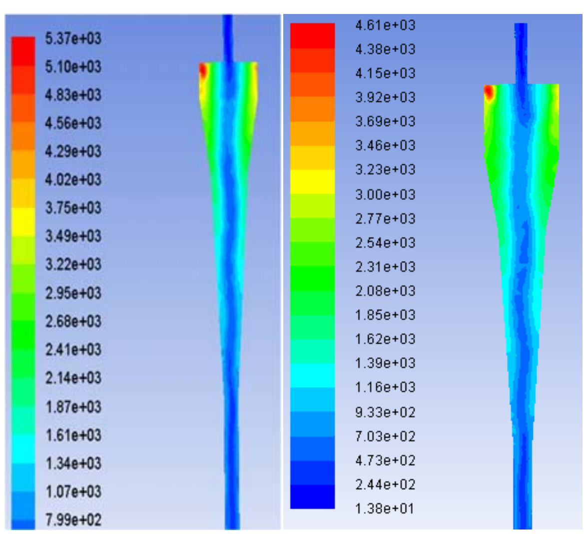
RESULTS AND DISCUSSIONS

Pressure distribution

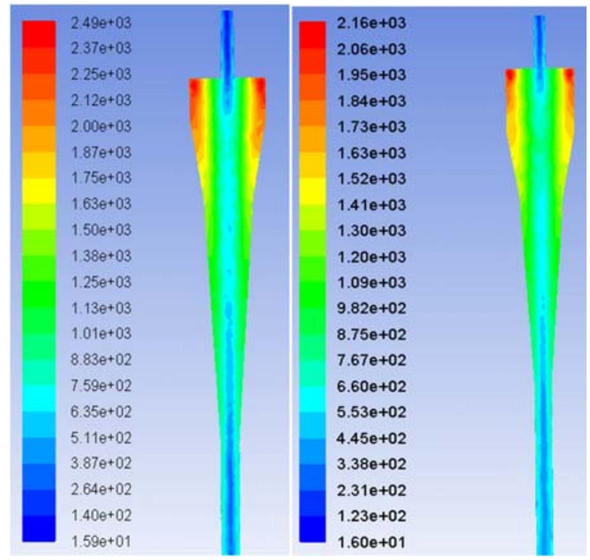
The pressure distributions within the four hydrocyclone types were investigated in order to understand the influence that the studied lengths and the number of inlets can bring. The CFX results are presented in Figure-4. In all the diagrams in Figure-4, pressure decreases radially from the cyclone wall to its core as also observed by [2]. The pressure is highest at the fluid entry and dies down as the fluid progresses down the cyclone. The lowest pressure zone at the core of the hydrocyclones is where the reversal flow exists and it is this area that contains the oil rich fraction of the separated fluid.

Even though the total pressure at the core of the hydrocyclones is generally low, the order of decreasing core pressure is as follows: single inlet 30 mm UCL hydrocyclone > single inlet 60 mm UCL hydrocyclone > dual inlet 30 mm UCL hydrocyclone > dual inlet 60 mm UCL hydrocyclone.

This highest core pressure observed in the single inlet 30 mm upper cylindrical hydrocyclone will cause the flow of more of the oil-rich fraction concentrated at the core to be pushed via the vortex finder compared with the other cyclones. However, it should be noted that the pressure at the core of the hydrocyclone is not the only contributor to the performance/efficiency of the hydrocyclone separator.



(a) (b)



(c) (d)

Figure-4. Pressure contour within the LLHC types: (a) single inlet 30 mm UCL (b) single inlet 60 mm UCL (c) dual inlet 30 mm UCL (d) dual inlet 60 mm UCL

Velocity distribution

The velocity distribution within the hydrocyclone is impacted by the rate at which the fluid swirls or spirals when it enters the cyclone. Study was done into the velocity profiles that existed in the hydrocyclone types. Figure-5 shows the axial velocity profile in the single- and dual-30 mm UCL hydrocyclones taken at different axial locations. The single inlet hydrocyclone is characterised by asymmetric profiles especially near the entry and progresses downward even though the upper cylindrical column is supposed to help stabilize the flow [3]. This behaviour is as a result of the fluid entering from only one side of the vertical axis [16]. The opposite scenario is observed in the dual inlet 30 mm UCL hydrocyclone. The two tangential inlets give symmetrical axial velocity profiles throughout the hydrocyclone with their highest points centralised at the core. This kind of pattern makes the reversal flow not to waver along the core as can be seen in the former case. Similar flow behaviours manifested in the case of the 60 mm UCL hydrocyclones.

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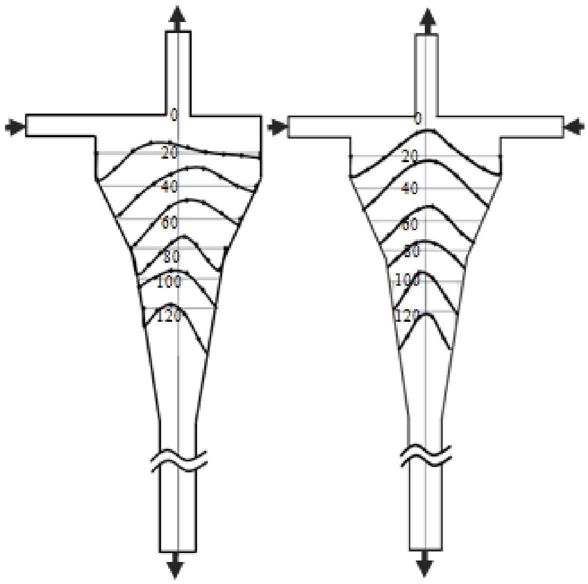

Figure-5. Axial velocity distribution in 30 mm UCL hydrocyclone: (a) single inlet; (b) dual inlet.

In order to clearly see the intensity of the axial velocity at the various axial locations, Figure-6 was made. The axial location, z = 20 mm, was chosen to make the point. The figure compares the axial velocity profiles of the studied hydrocyclone types at the said axial location together with some data from Chang and Dhir's work [17] at similar axial position.

By observing Figure-6, the single inlet hydrocyclones have their peak velocities skewed to one side (left) whereas the dual inlet ones have their peak velocities uniformly distributed across the cyclone axis which is in agreement with Chang and Dhir's works with an even number of inlets, the reason of which has been explained in the earlier paragraph. However, the single inlet- and dual inlet- 30 mm UCL hydrocyclones record greater axial velocity when compared with the single inlet- and dual inlet- 60 mm UCL hydrocyclones respectively. The higher the axial velocity, the better the upward movement of the reversal flow at the core.

The tangential velocity distributions across the axial locations of the studied hydrocyclone types are as presented in Figure-7. The tangential velocity is an important velocity component within a hydrocyclone as it is the force behind the centrifugal acceleration that causes segregation of the fluid particles inside the cyclone.

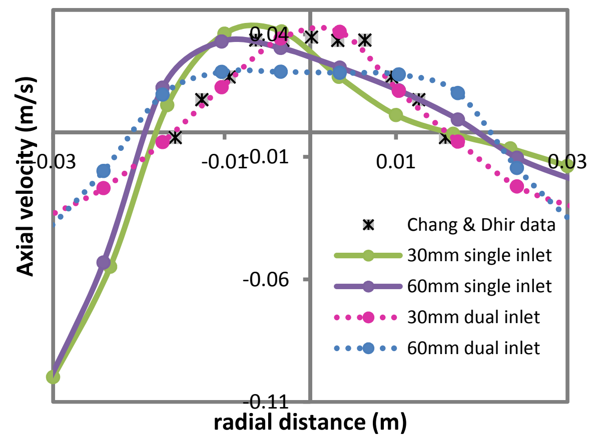

Figure-6. Axial velocity comparison at z = 20 mm.

The tangential velocity is a combination of the forced vortex and the free vortex [2, 5], and their widths depend on the swirl intensity distribution along axis of the cyclone [18]. The magnitude of the tangential velocities can also be influenced by the feeding rate as pointed out by [15].

In Figure-7, the swirl intensity has caused the tangential velocities to rise from the axis of the cyclone to a height after which the velocities drop down to zero at the walls. Most of the velocity profiles in the single inlet hydrocyclone are decentralised about the axis of the cyclone due to the one entry it has. This is cause of the snakelike upward reversal flow that can be observed in Figure-4a and -4b. Nevertheless, the twin inlet cyclone presents its velocities almost symmetrical across the studied axial locations. The number of tangential inlets of a cyclone therefore can influence the stability of the fluid inside the hydrocyclone as it swirls and rotates.

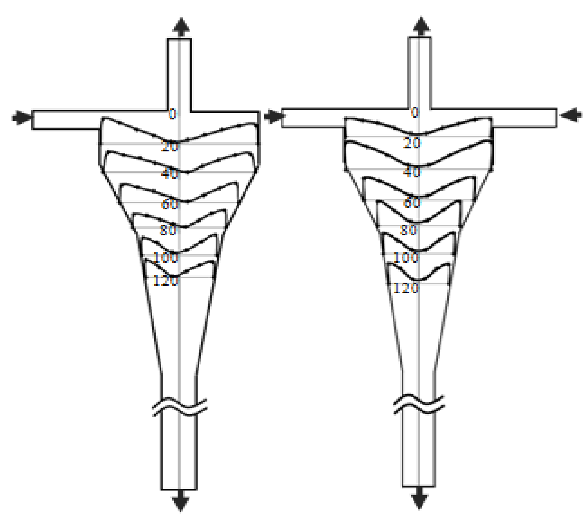

Figure-7. Tangential velocity distribution in 30 mm UCL hydrocyclone: (a) single inlet; (b) dual inlet.

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In order to make clear the contribution of the tangential velocities at a given axial location, Figure-8 has been presented. This figure compares the tangential velocities of the studied hydrocyclones at axial location, z = 20 mm. The single inlet cyclones generally record higher velocities than their dual inlet counterparts. However, by making single to single and dual to dual comparison, the better one stands out. The single inlet 30 mm UCL hydrocyclone shows greater tangential velocity magnitude than the single inlet 60 mm UCL hydrocyclone which means that the former has greater swirling ability at z = 20 mm than the latter. The dual inlet 30 mm UCL hydrocyclone also shows its supremacy over the 60 mm UCL type. This shows how the 30 mm UCL cyclones perform better than the 60 mm UCL types. However, the single inlet 30 mm UCL hydrocyclone aside its asymmetrical pattern performs far better the dual inlet 30 mm UCL type and it also fairly agrees in normalised velocity magnitudes from Chang and Dhir's work [17] than the others.

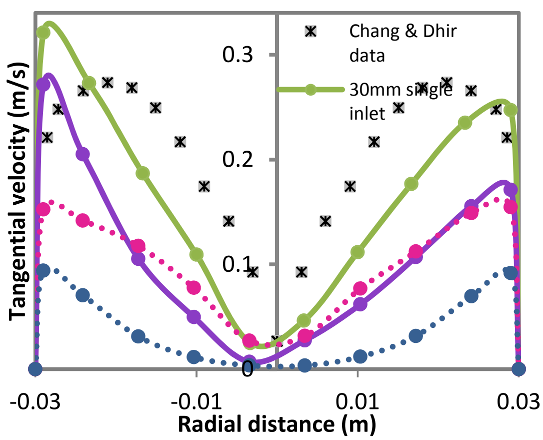

Figure-8. Tangential velocity comparison at z = 20 mm.

CONCLUSIONS

In this paper, numerical simulation was done to study the internal flow fields of a novel hydrocyclone to handle oil and water. The single inlet hydrocyclones produced asymmetric velocity profiles giving wavy inner core region. In this situation there is a high tendency of the upward reversal flow to carry along some fluid particles that fall outside the core zone and affect the efficiency of the separation process. The dual inlet hydrocyclones on the other hand gave perfect symmetrical velocity profiles about the axis of the cyclone and did not disturb much fluids falling outside the core zone. Moreover, the 30 mm UCL hydrocyclones all produced higher velocity profiles (both axially and tangentially) than the 60 mm types and this is important for ensuring better swirling and upward reversal flow. The single inlet 30 mm UCL hydrocyclone produced the highest velocity fields that can ensure better fluid swirling and rotation and also maintained the greatest upward core flowing pressure that can ensure better transportation of the lighter fraction concentrated at the core. The single inlet 30 mm UCL hydrocyclone was therefore the best type out of the studied hydrocylone types and can ensure promising separation performance. Further work must therefore be done on the separation capabilities of these LLHC types.

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